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RESEARCH MEMORANDUM

DESIGN CONSIDERATIONS OF A CONDENSING SYSTEM FOR VAPORIZED MAGNESIUM

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

An investigation of various condensing chambers for vaporized magnesium was conducted to determine the effect of design characteristics on magnesium build-up at the chamber inlet. The condensing chamber is a portion of the apparatus used in preparing magnesium slurries by the vapor-condensation process. A complete description of the various chamber designs and the procedure used in testing the chambers is given.

The chambers were compared on the basis of clogging and total magnesium distilled per run. The effect of orifice design on clogging was also considered. Proper insulation and heating at the chamber inlet were found to be important. Flow in transparent models indicated recirculation to be present.

INTRODUCTION

Theoretical and experimental combustion studies at the NACA Lewis laboratory have indicated that higher thrusts can be obtained from ram jets and afterburners with concentrated suspensions of magnesium in hydrocarbons than with conventional jet fuels. Additional investigations have shown that blow-out velocities and combustion efficiencies of magnesium slurry fuels increase as the particle size of the magnesium in the slurry fuels decreases (ref. 1).

The most practical and most promising method of producing magnesium slurries having high blow-out velocities and high combustion efficiencies is by shock-cooling magnesium vapors with a suitable hydrocarbon (ref. 2). A modification of this system was made in order to increase the operating time by increasing the capacity of the system. However, the increased capacity of the system did not give an appreciable increase in the operating time, the reason again being, as in reference 2, magnesium deposition or clogging in the condensing-chamber inlet. Clogging occurs when some of the magnesium vapors, which flow through an orifice into the chamber, condense around the chamber inlet and eventually plug the opening. Because of this clogging problem, a comprehensive study was made of various condensing-chamber designs.

For this design study, various condensing chambers were made of both steel and Lucite. In conjunction with the high-temperature work using the steel chambers, flow patterns were observed in the Lucite chambers by blowing balsa dust through the orifice into the condensing chamber (ref. 3).

This report describes the condensing chambers tested, gives the results on clogging obtained with respect to chamber design, and evaluates the various chamber designs from the results.

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PROCESS AND APPARATUS

Process

Magnesium metal was vaporized by heating to about 2000° F. Hot helium was introduced to maintain a pressure of about 11 pounds per square inch gage in the vaporizing pot. The magnesium vapors passed through a heated orifice into a condensing chamber where the metal vapors were condensed into minute particles of solid by a series of hydrocarbon sprays. The solid particles and liquid hydrocarbon were separated from the helium and gaseous hydrocarbon, and the resulting slurry was concentrated and then stored (ref. 2). A pressure above atmospheric was maintained throughout the entire system in order to prevent leakage of air into the unit.

Apparatus

The bulk of the equipment used in the vaporization unit was similar to that used in reference 2 (fig. 1). In order to increase the capacity of the system, some modifications were made. The increased capacity was obtained by enlarging the vaporizing pot, installing a 750-gallon storage tank for the dilute slurry, installing an automatic pumping device for removing the dilute slurry from the product receiver to the storage tank, and recycling the effluent from the centrifuge.

In order to decrease the hazard of handling the final product, the condensing medium was changed from JP-1 fuel (ref. 2) to a mixture of 90 percent by volume JP-1 fuel and 10 percent by volume number 2 fuel oil (table I).

Condensing chambers. - The experimental condensing chambers considered in this report are shown in figure 2. With the exception of chamber I, which was the condensing chamber used in reference 2, the various chambers tested were designed with either a flanged back plate or a flanged connection near the chamber outlet. Incorporating these flanges into the

various chambers made it possible to remove the magnesium deposits from the chambers without completely dismantling the condensing system. The spray nozzles in chambers I, II, and V were so situated that the magnesium vapors entering the chamber would pass through a series of three hydrocarbon sprays. In the design of these chambers, the orifice outlet and the spray nozzle nearest this outlet were so positioned that the spray would not come in contact with the orifice outlet. The orifice outlets for these three chambers were either flush with the inside surface of the chamber or slightly recessed.

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The main feature in the design of chambers III-A and III-B was the washing of all surfaces near the magnesium-vapor inlet by the hydrocarbon sprays of three spray nozzles equally spaced on the cone-shaped portion of the chambers. These two chambers differed only in that in chamber III-B an extension was substituted for the blind flange on chamber III-A.

Chamber IV had two sets of three spray nozzles arranged in the same plane so that each set of nozzles sprayed on the opposite wall. This spray-nozzle arrangement made it possible to flush the entire inside of the chamber with hydrocarbon. The desired feature in this chamber design was to prevent recirculation by streamlining the chamber.

Chamber V was made of a section of standard 6-inch pipe. A comparison of all the chambers tested shows that the frontal area of chamber V is greater than that of any of the other chambers. Following several initial tests with this design, the inside surface at the inlet end of the chamber was insulated. This insulation consisted of a $1\frac{1}{2}$-inch outside diameter by 1/2-inch inside diameter by 1/4-inch thick ring of alundum around the orifice and 1/4-inch-thick cement-asbestos board on the remainder of the inside surface. The orifice connected to this chamber was flush with the exposed surface of the insulation. High-temperature furnace cement was used to seal all openings or cracks on the insulated surface.

The induction coil at the condensing-chamber inlet for all chambers tested was so arranged that the temperature at the orifice outlet during all runs was above the melting point of magnesium. This was accomplished in chamber V by heating the entire inlet end of the chamber, thus reducing the heat loss from the orifice outlet. In chamber IV the final turn of induction coil was 1 inch from the first set of spray nozzles.

Orifices. - Three orifices were used in the testing of the various condensing chambers (fig. 3). Orifice Z is discussed in reference 2 as a converging-diverging orifice. Several of the condensing-chamber tests were made using orifice Y. This orifice is a 1/2-inch outside diameter by 3/16-inch inside diameter tube with a cone-shaped outlet made

of stainless-steel cloth through which hot helium could be passed. The majority of the tests were made with orifice X. Because of the extreme temperature conditions the orifice must withstand, orifice X was usually heavy-wall tube with the dimensions 1/2-inch outside diameter by 3/16-inch inside diameter by $7\frac{1}{2}$-inches long.

PROCEDURE

High-Temperature Studies

The operation of the system was similar to that described in reference 2, the main exception being a completely pressurized system as suggested in reference 2. Whenever possible, union-type fittings were used to facilitate change-over from one chamber and orifice combination to another. The number of runs made with each combination depended on its performance. The data from three typical runs are given in table II.

Following each run, the condensing chamber was inspected to determine the type and severity of the plug. In addition, the total amount of magnesium distilled during the run was determined from the amount of metal in the pot before and after the run.

Flow-Pattern Observations

Balsa dust carried by an air stream into the transparent chamber models provided visual observation of solid-particle flow. The balsa dust was injected into an air stream and then carried through an orifice into the chamber being tested. Photographic traces of the balsa-dust particles in a relatively narrow zone through the centerline of the chamber were obtained by using a camera together with a stroboscopic lamp (ref. 3).

DISCUSSION OF RESULTS

In this series of tests, magnesium deposition always occurred. Empirical studies indicated that this deposition resulted from (1) the diffusion of the metal vapors and the recirculation of magnesium particles condensed in the hydrocarbon spray, and (2) the presence of relatively cool surfaces. Major improvements were expected from changes in design of the condensing chamber and orifice and through the application of heat at critical clogging areas.

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DESIGN PARAMETERS

Effect of condensing-chamber design. - Chambers for condensing magnesium vapors were designed primarily for a sudden and continuous interaction of metal vapors with hydrocarbon liquid. This function was readily carried out in the designs described in this report; the fineness of solid particles in the product served as a measure of the efficiency of the condensing operation.

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The interaction of vapor and condensing liquid was made to occur as close to the orifice outlet as possible without cooling the orifice. There was a tendency for the magnesium to build a formation at the chamber inlet that would eventually plug the system. This build-up occurred on surfaces that had a temperature near or below the melting point of magnesium and were not washed by the hydrocarbon liquid. In chamber IV, where the metal vapors were allowed to expand gradually, the walls at the edge of the heated zone were apparently cool enough to cause solidification of the magnesium at this point and quickly block the passage leading to the hydrocarbon sprays. In the other designs, where the orifice ended abruptly in a large chamber, the walls were more remote; the flow was turbulent and subject to recirculation. The magnesium formations at the chamber inlets in these designs were considered to be due partly to vapors solidifying at the inlets and partly to deposition of metal particles that circulated to the inlets. Changes in the condensing-chamber design were made in an attempt to reduce these temperature and recirculation effects.

The chamber designs in this investigation were compared on the basis of the amount of metal distilled per run. Variations in distillation rates made it impractical to use the "on-stream" time per run as the measure for comparison. As shown in table III, for those runs in which the pot was not emptied, the amount of magnesium distilled varied from 0.3 to 9.9 pounds of metal per run. Runs in which more than 5 pounds of metal were distilled were usually considered good.

Evaluation of the data given in table III rated the freedom from clogging, or the productive potential, of each condenser as follows:

Condensing-chamber design	Freedom from clogging
I	Fair
II	Poor
III-A	Fair
III-B	Good
IV	Very poor
V(uninsulated)	Very poor
V(insulated)	Very good

Chamber I was rated as having produced a fair amount of product before magnesium deposition interrupted its operations. However, several runs with chamber I using orifice Y took longer to plug than usual for this chamber, perhaps because of the larger opening to be sealed. On the contrary, chamber III-A using orifice Y gave very poor operating results. Streamline flow of the magnesium vapors into chamber IV gave very poor results, although clogging may have been due entirely to the cooling effect of the hydrocarbon sprays. Good results were obtained in chamber III-B, the elongated version of III-A; the circumferential treatment of the sprays on the cone part of the chamber (fig. 2) tended to confine the clogging to the small area about the chamber inlet. Because of plugging in the orifice outlet, chamber V operated only for short intervals; the on-stream time of this chamber was increased tremendously by proper insulation and heating.

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Effect of insulation in chamber V. - The productive capacity of condensing-chamber V was effectively increased from 10 to 15 times through insulation of the inlet section in the chamber. Prior to insulating the chamber inlet, short runs were caused by plugging in the orifice outlet. This plug was attributed to heat losses from the orifice tube. The heating coil was extended to heat the entire inlet portion of the chamber, but a large amount of heat loss was still encountered because of the cooling effect of the hydrocarbon spray. Several attempts at insulating the hot surface from the cold liquid netted the simple but effective insulating method described in the Apparatus section and shown in figure 2. Except for the very tip of the orifice tube, the insulating wall prevented direct cooling of the orifice tube. Heat losses from the orifice tube by conduction were reduced greatly by increasing the conductive distance and buffering this space with heat. Although the objective of maintaining an orifice-outlet temperature higher than the melting point of magnesium was made possible through insulating the chamber inlet, clogging still occurred. However, the build-up of magnesium powder at the chamber inlet was retarded so that, in a large percentage of runs, the magnesium pot could be emptied of a 15- to 17-pound charge.

Effect of orifice design. - In reference 2 it was established that a restriction, or orifice, was required to prevent plugging of the piping from the vaporizing pot by coke formation from hydrocarbon vapors that entered the heated zone. The orifice was further used to guide the metal vapors directly into the hydrocarbon spray. Clogging in the orifice outlet by magnesium deposition (fig. 4) usually occurred in the early test runs. This problem was minimized through adjustment of the heat applied to the orifice section. This maneuver shifted the clogging into the chamber. In order to prevent a build-up of magnesium at the tip of the orifice outlet, the tip temperature had to be maintained above the melting point of magnesium.

None of the three orifice designs tested showed any exceptional qualities with respect to clogging. In all three cases the position of magnesium deposition could be shifted from the orifice-tube outlet to some position in the chamber (very close to the orifice) by changing the heating coil arrangement. From a standpoint of fabrication, orifice X was considered the best design. Orifice Y showed some tendency for condensation on the wires of the screen cone, but this tendency proved unimportant because a plug normally resulted from a cap formed at the end of the cone (fig. 4(f)).

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General Observations

Clogging. - The size, shape, and rate of the magnesium formation varied with each run and could not be readily duplicated. Although the diffusion of magnesium vapors and the back flow of the condensed metal particles played an important role in determining the character of this formation, the amount of heat and the area where it was applied influenced the time required to plug the system. A plug could occur immediately after going on-stream if insufficient heat was supplied to the orifice tube (fig. 4(a)). This type of plug was satisfactorily eliminated by maintaining the entire length of the orifice at a temperature higher than the magnesium melting point. Usually this temperature was kept around 1600° F.

An extreme example of clogging (fig. 4(b)) occurred during several runs as a result of extending the heating coil too far beyond the chamber inlet. This severe form of magnesium deposition also took place when the hydrocarbon spray nozzle closest to the inlet was eliminated; the formation extended from the first active spray nozzle back to the inlet. Apparently, as the heating was extended farther down the chamber, there was a greater area available at the intermediate temperature required for magnesium deposition; therefore, a larger-than-usual build-up of magnesium occurred.

It was interesting to note that little or no deposition of magnesium was found on the chamber walls washed by the hydrocarbon spray. However, attempts to confirm this lead and prevent magnesium formation by washing the chamber inlet with the condensing liquid led to solidification of the metal vapors in the orifice outlet.

Another example of a large magnesium formation was noted at times in one particular chamber, and was found to be composed entirely of soft powder (figs. 4(c) and 5(a)). This condition resulted from condensed metal particles traveling across chamber III-A, colliding with the blind flange, and proceeding to form a growth toward the orifice. As shown in figure 5(a), the growths would break off during the run until one successfully plugged the opening of the orifice. The remedy for this form of

clogging consisted in increasing the chamber length so that the metal particles could be carried away by the hydrocarbon before they could travel across the chamber (chamber III-B).

Very little useful product was prepared from runs in which the three preceding plug types occurred. Severe depositing meant most of the condensed magnesium remained in the chamber, and a clogged orifice outlet prevented the production of any useful material.

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Longer running time and sizeable quantities of product usually were obtained in runs where a stubby protrusion was found at the chamber inlet on shutdown (figs. 4(d), (e), and (f)). In test runs in which the vaporizing pot was emptied of magnesium, the condensing-chamber inlet was ordinarily found with the hollow protrusion shown in figure 4(d). The opening in the plug was approximately that of the diameter of the orifice. In relatively long runs where the pot pressure rose to indicate a clogged system, the chamber displayed a protrusion of magnesium that had been hollow but eventually became filled with crystallized metal (figs. 4(e) and 5(b)). It was assumed that the hollow protrusion would build out until contact was made with the hydrocarbon spray whereupon the magnesium tube became sealed, and the metal vapors crystallized in the closed tube. The use of a screen-cone orifice normally produced a thin powdery cap behind which the magnesium vapors changed to crystals (fig. 4(f)).

Visual Flow Observations

Attempts to observe the build-up of magnesium in the high-temperature setup were not successful; therefore, transparent chambers were used. The condensation of petroleum-wax vapors by water sprays showed that visual observation of any deposition would be greatly hindered by the action of the condensing-liquid spray.

In order to illustrate that a portion of the condensed magnesium particles could readily contribute to the deposits at the chamber inlet, balsa dust was used. Observations of balsa-dust flow patterns in transparent models of some of the chamber designs showed recirculation of those particles. Because of the difficulties in observing flow patterns in the magnesium-vaporization unit, it was felt that flow patterns of the dry balsa particles gave some idea of the turbulent condition in the condensing chamber during an actual run.

Nature of Product

Despite efforts to prevent air leakage into the system, the purity of the condensed magnesium product generally ran about 90 percent free

magnesium metal. However, even with 10 percent oxide present in the product, the concentrated slurry gave better blow-out velocities in a combustor than several other slurries containing larger magnesium particles of high purity (ref. 4). The improved combustion properties of this slurry were attributed to the large quantity of fine particles present. Surface-active additives were required to reduce the agglomeration of the fine magnesium particles. An electron micrograph of some of the particles prepared in the insulated version of chamber V is shown in figure 6. The size of the particles in this field ranged from 600 to 1800 A in diameter; occasionally larger particles up to 4300 A were found in this sample. The particle size range was estimated from an electron micrograph prepared at the Dow Chemical Co. laboratories, Midland, Michigan.

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CONCLUDING REMARKS

At present it is difficult to visualize the complete elimination of magnesium deposition at the condensing-chamber inlet. Further investigations of this problem could be expected to retard the metal-powder build-up to the point where it would not seriously affect the operation of a continuous process. A larger unit would also be expected to operate more satisfactorily than the present setup. Retarding diffusion of the magnesium vapors and recirculation of the condensed particles and maintaining the vapor-traveled areas at temperatures above the melting point of magnesium should be given primary consideration in the design of a condensing system for vaporized magnesium slurries.

SUMMARY OF RESULTS

Clogging due to magnesium deposition at the condensing-chamber inlet of the magnesium vaporization unit has been a continuous problem. Investigation of the causes and possible elimination of this problem was made using various condenser designs.

Observations of magnesium deposits and observations of balsa-dust patterns indicated that clogging came from the diffusion of the metal vapors and the recirculation of condensed magnesium particles to the cool, dry, condensing-chamber wall surfaces where the metal adhered and eventually blocked the orifice. Insulation of the inner face of the chamber inlet to hold the face and orifice-outlet temperatures above the melting point of magnesium was effective in minimizing magnesium-metal deposits.

Attempts to reduce recirculation by changes in chamber shape and orifice design did little toward solving the problem. The most effective

of the several designs investigated was a cylindrical chamber with insulation internally mounted at the end through which magnesium vapor entered.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 21, 1955

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4. Morris, James F., Caves, Robert M., and Lord, Albert M.: Blow-Out Velocities of Several Slurry and Liquid Fuels in a $1\frac{7}{8}$-Inch-Diameter Combustor. NACA RM E54L27a, 1955.

TABLE I. - ANALYSIS OF CONDENSING MEDIUM (MIXTURE OF 90 PERCENT BY VOLUME MIL-F-5616, GRADE JP-1, FUEL AND 10 PERCENT BY VOLUME NUMBER 2 FUEL OIL)

A.S.T.M. distillation D86-52, °F	
Initial boiling point	339
Percentage evaporated	
5	343
10	349
20	354
30	361
40	368
50	375
60	385
70	395
80	411
90	445
95	487
Final boiling point	554
Residue, percent	1.4
Loss, percent	0.6
Specific gravity	0.806
Gravity, °A.P.I.	44.0
Viscosity at 77° F, centistokes	1.588

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TABLE II. - TYPICAL RUN DATA FOR MAGNESIUM VAPORIZATION UNIT

Run	1	2	3
Chamber	III-A	V(Insulated)	V(Insulated)
Orifice	X	X	X
On-stream time, min	117	250	353
Pot pressure, lb/sq in. gage	12.0	12.4	10.7
Helium flow, lb/hr	5.27	2.20	3.97
Flow of condensing medium in chamber, gal/hr	22.5	72.0	72.0
Magnesium liquid temperature (av.), ^{o}F	1750	1950	1925
Helium temperature (av.), ^{o}F	1350	1410	1390
Chamber-inlet coupling temperature (av.), ^{o}F	840	1700	1900
Distillation rate, lb/hr	2.3	2.1	2.8
Amount distilled, lb	4.4	8.8	16.6
Reason for ending run	Clogged inlet	Clogged inlet	Pot appeared empty

TABLE III. - SUMMARY OF DATA FOR CONDENSING SYSTEM OF MAGNESIUM VAPORIZATION UNIT

Condensing chamber, type	Orifice			On-stream time per run, min		Total amount distilled per run (av.), lb
	Type	Throat size, in.	Number of runs, (a)	Range	Av.	
I	X	1/8	1	-------	94	[b]3.3
	Y	3/16	4	142-211	179	[b]6.3
	Z	3/32	5	59-138	97	[b]3.4
	Z	1/4	1	-------	73	2.6
II	X	3/16	3	59-79	72	[b]2.5
III-A	Y	3/16	2	51-57	54	[b]1.9
	X	1/8	[c]2	181-255	218	5.6
	X	3/16	3	117-139	131	[b]4.0
	X	3/4	3	67-110	94	[b]3.4
III-B	X	3/16	2	136-169	152	6.1
	Z	1/4	1	-------	156	[b]5.5
IV	X	1	1	-------	31	0.3
	Z	1/4	1	-------	47	1.8
V(Uninsulated)	X	3/16	3	16-44	27	[b]1.0
V(Insulated)	X	3/16	11	155-309	232	9.9
	X	3/16	[c]8	275-375	328	16.2

[a]All runs ended because of clogging except where indicated.

[b]Estimated from run data.

[c]Ended run because pot appeared empty.

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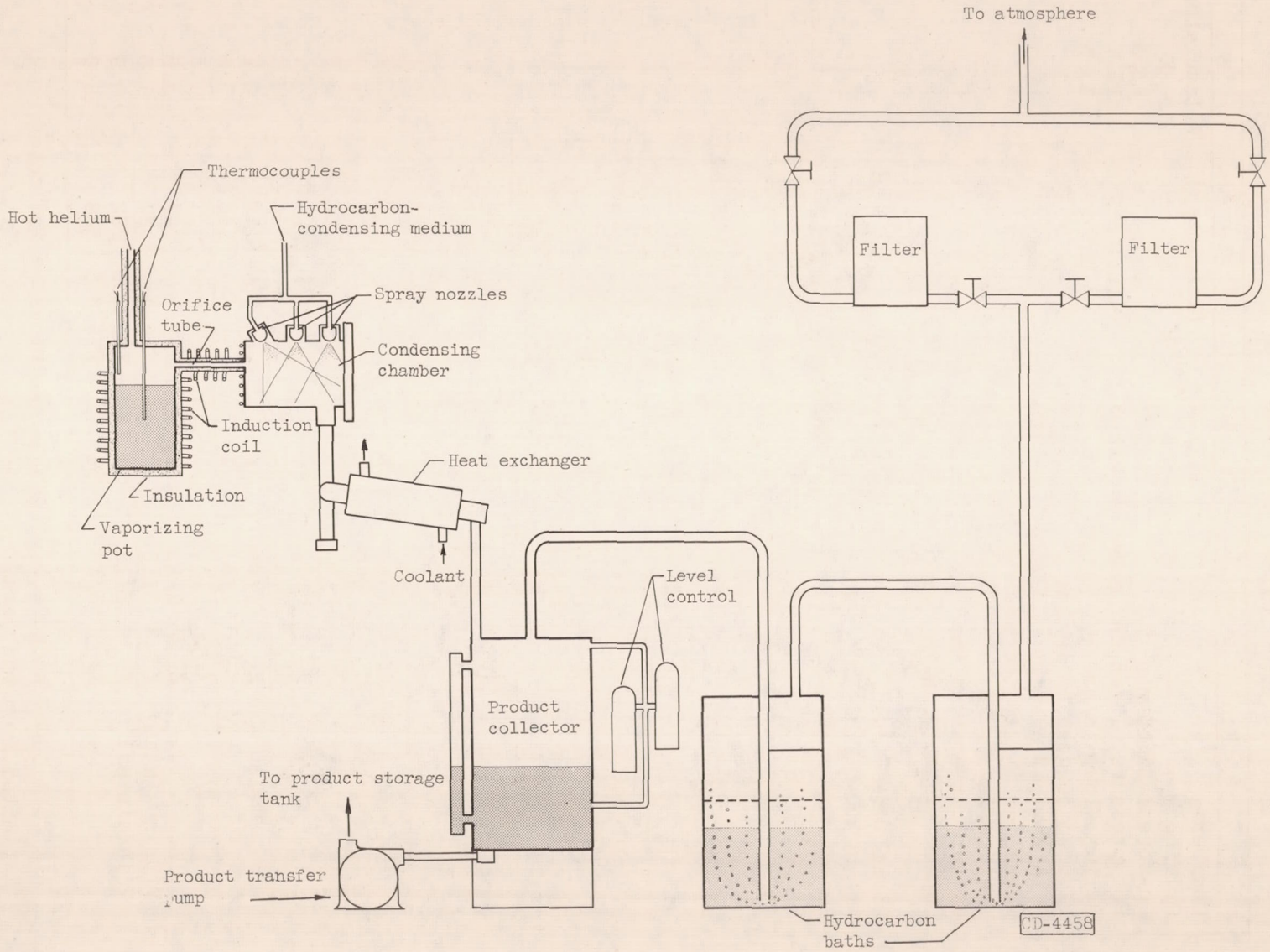
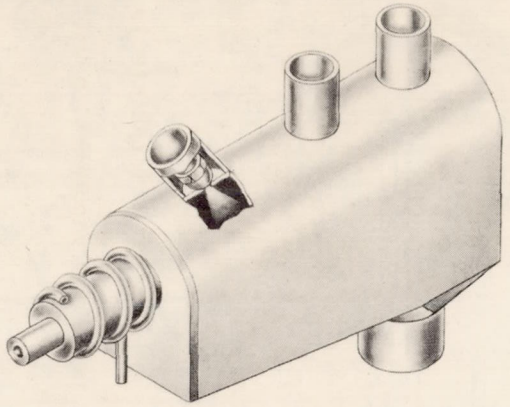
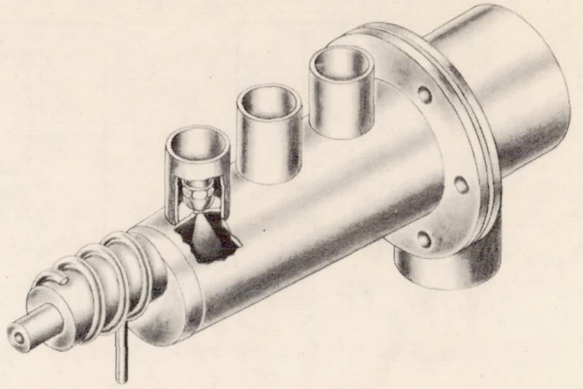


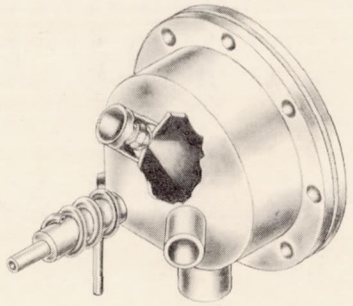
Figure 1. - Schematic diagram of magnesium vaporization unit.



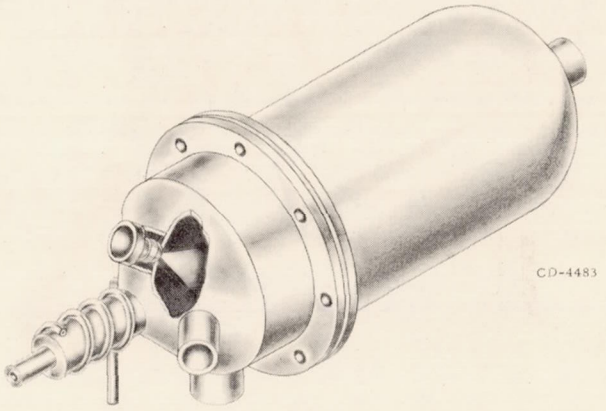
(a) Chamber I.



(b) Chamber II.



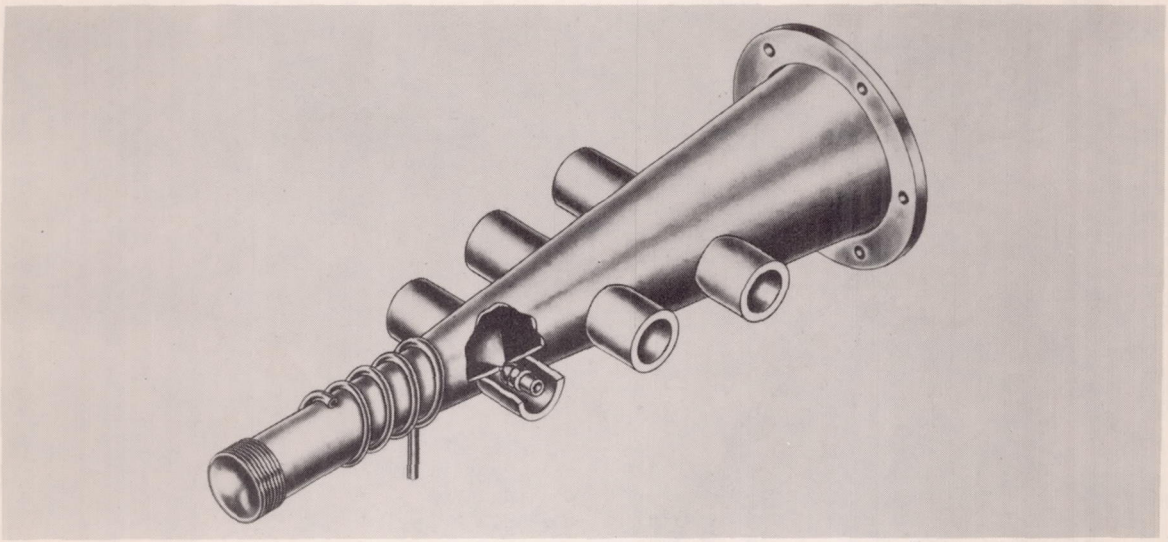
(c) Chamber III-A.



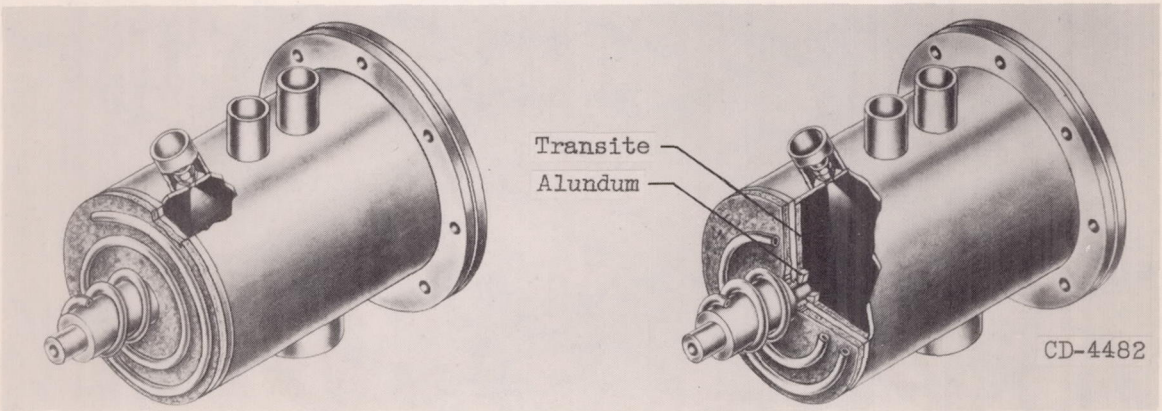
(d) Chamber III-B.

Figure 2. - Condensing chambers for magnesium vaporization unit.

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(e) Chamber IV.



(f) Chamber V (uninsulated). (g) Chamber V (insulated).

Figure 2. - Concluded. Condensing chambers for magnesium vaporization unit.

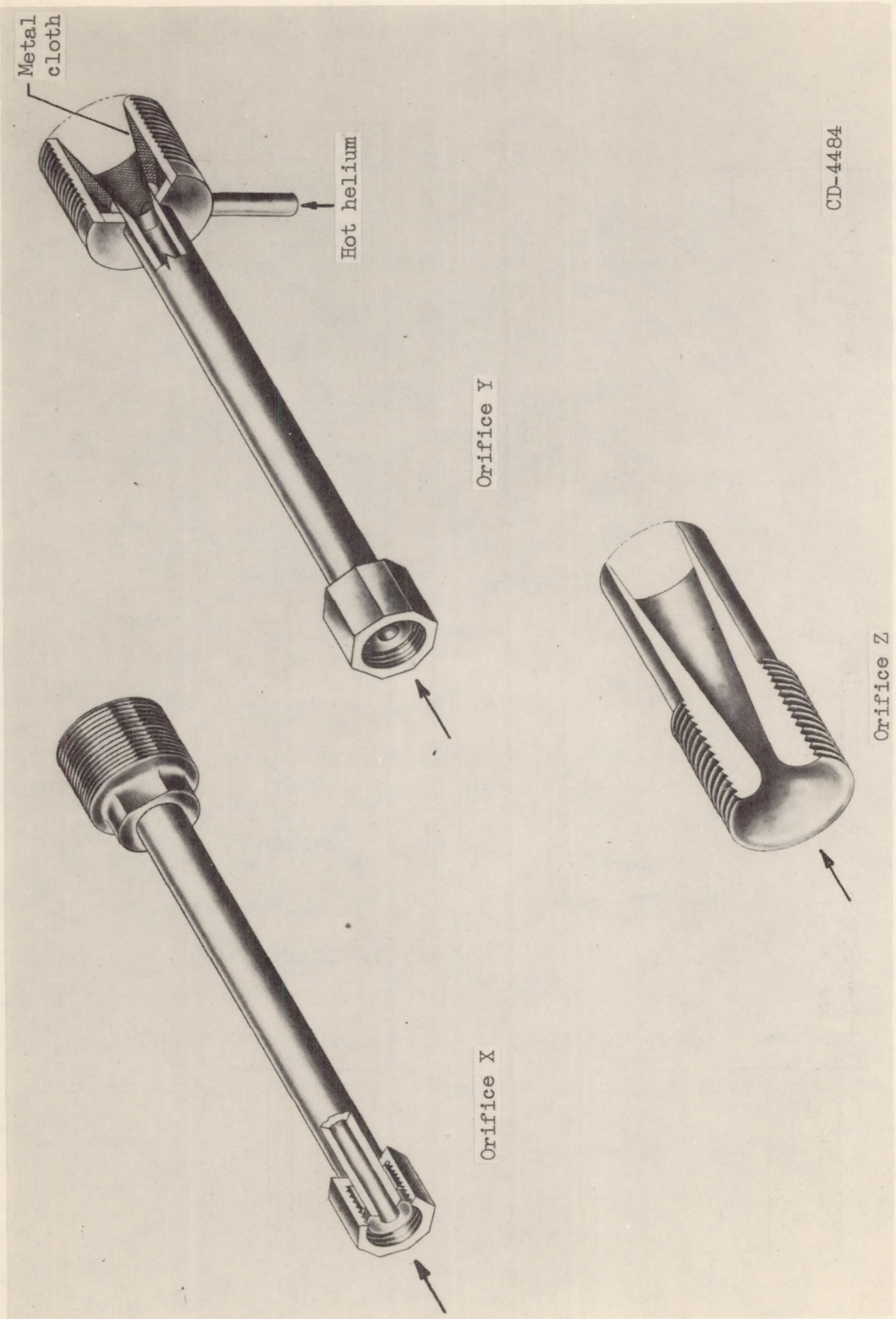


Figure 3. - Orifices used in the magnesium vaporization unit.

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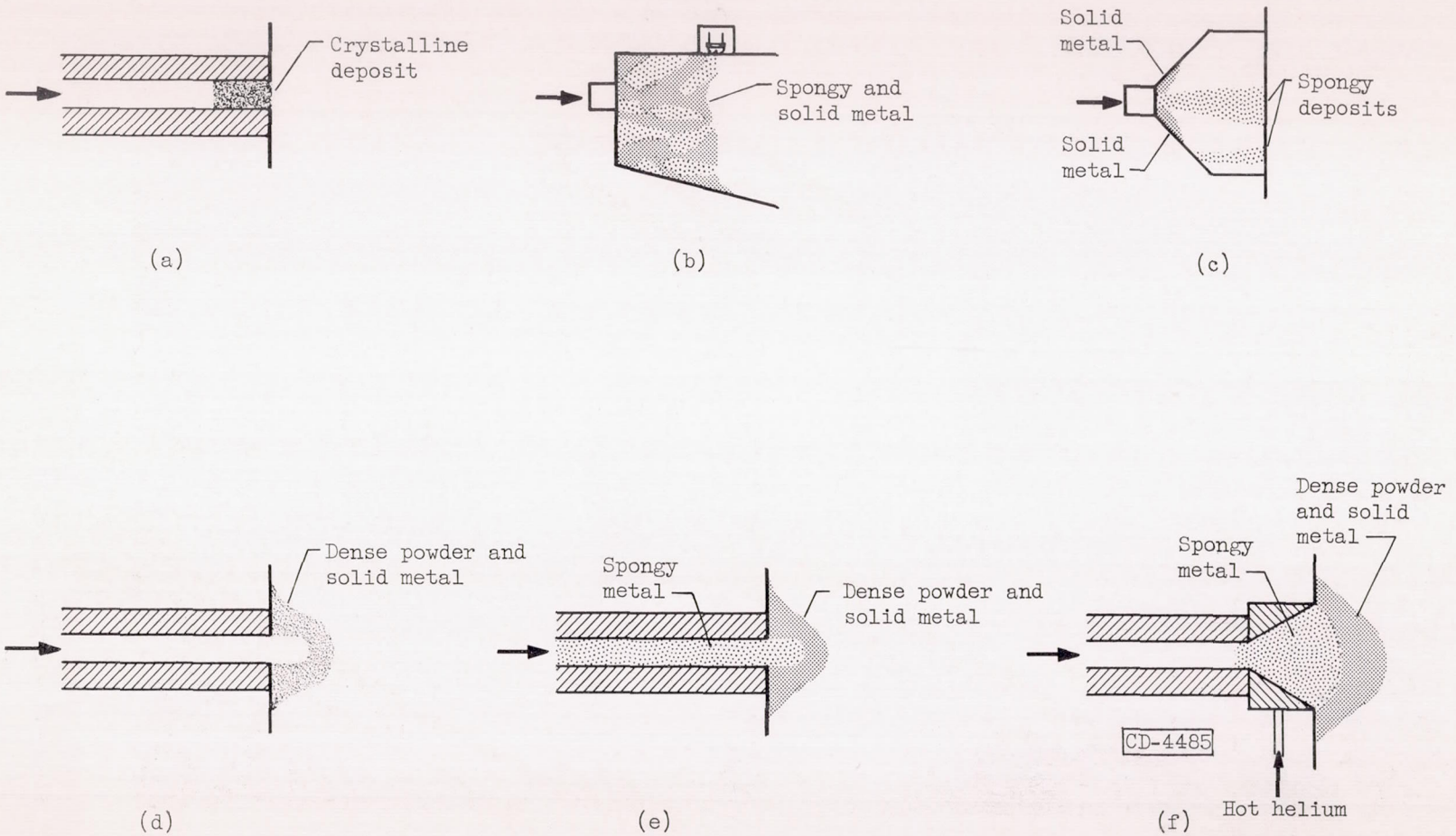
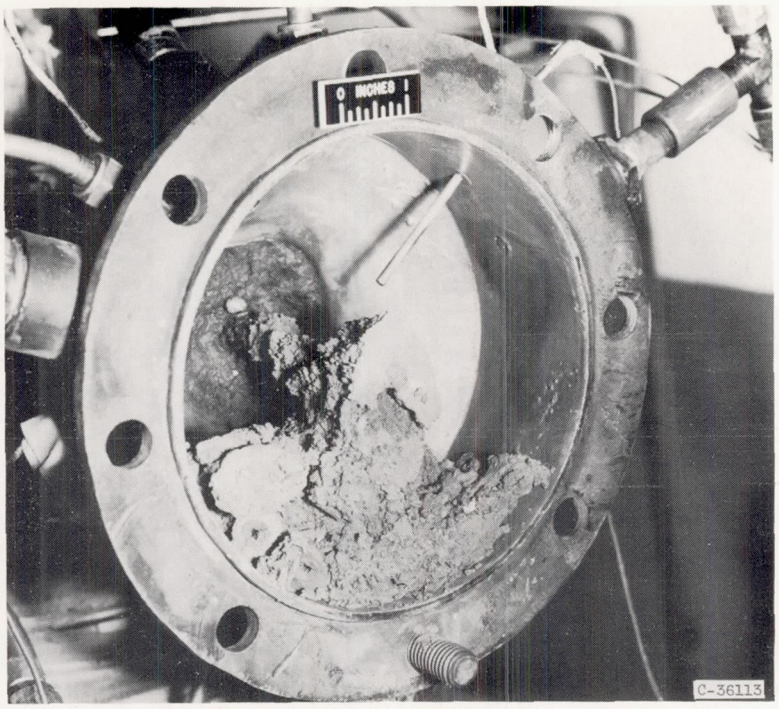
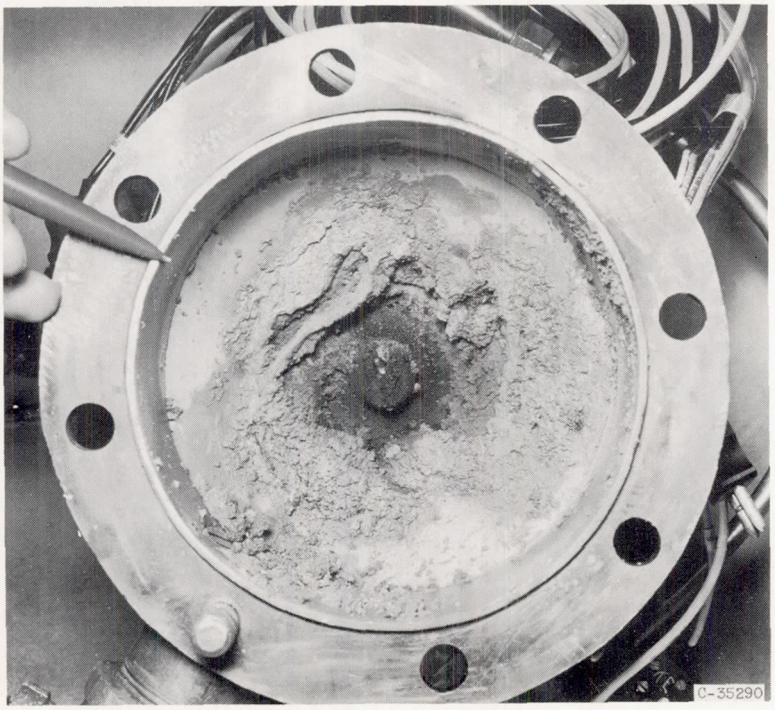


Figure 4. - Types of magnesium deposits observed in orifices and chambers after runs.

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(a)



(b)

Figure 5. - Typical magnesium deposits in condensing chamber.

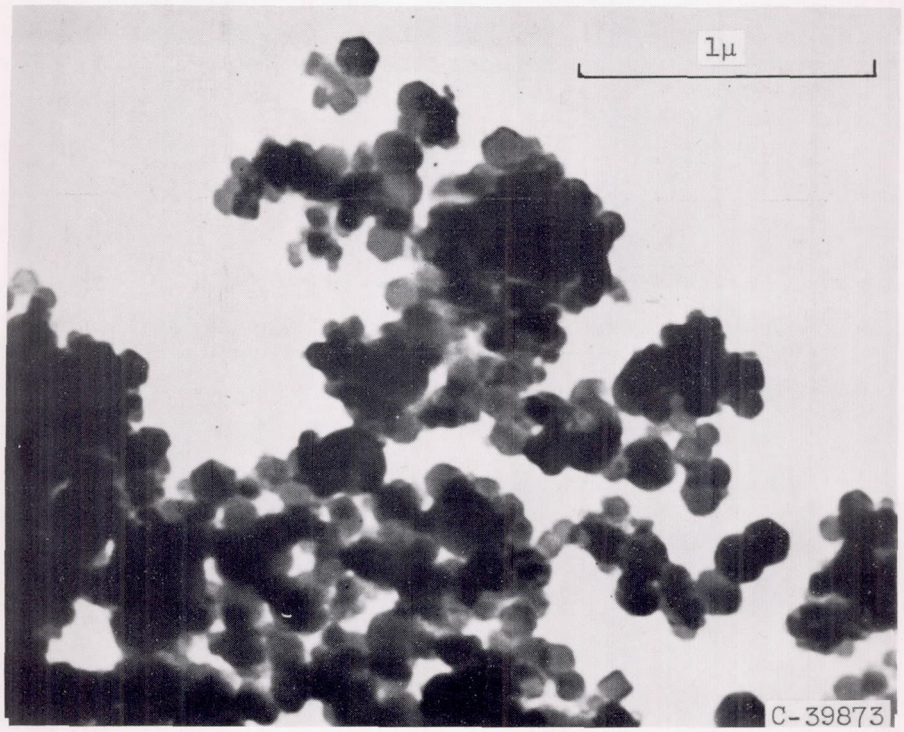


Figure 6. - Electron micrograph of fine particles condensed in magnesium vaporization unit X40,000.